hep-ph/0408083

Transverse beam polarization and limits on leptoquark couplings in $e^+e^- \to t\bar{t}$

Saurabh D. Rindani

Theory Group, Physical Research Laboratory
Navrangpura, Ahmedabad 380 009, India

Abstract

It is shown that if electron and positron beams at a linear collider are transversely polarized, azimuthal asymmetries of the final-state top quark in $e^+e^- \to t\bar{t}$ can be used to probe a combination of couplings of left and right chiralities in a scalar leptoquark model. The CP-conserving azimuthal asymmetry would be a sensitive test of the chirality violating couplings. A linear collider operating at $\sqrt{s} = 500$ GeV and having transverse polarizations of 80% and 60% respectively for the e^- and e^+ beams, can put a limit of the order of 0.025 on the product of the left and right chirality leptoquark couplings (in units of the electromagnetic coupling constant), with a leptoquark mass of 1 TeV and for an integrated luminosity of 500 fb^{-1}. The CP-violating azimuthal asymmetry, which would provide a direct test of CP-violating phases in leptoquark couplings, can be constrained to the same level of accuracy. However, this limit is uninteresting in view of the much better indirect limit from the electric dipole moment of the electron.

1 Introduction

An e^+e^- linear collider operating at a centre-of-mass (cm) energy of several hundred GeV will offer an opportunity to make precision measurement of the properties of the electroweak gauge bosons, top quarks, Higgs bosons,

and also to constrain new physics. Linear colliders are expected to have the option of longitudinally polarized beams, which can help to improve the sensitivity of these measurements and reduce background in the search for new physics. It has been realized that spin rotators can be used to convert the longitudinal beam polarization to transverse polarization. This has inspired studies which investigate the role of transverse polarization in constraining new physics [1, 2], though these studies are yet far from being exhaustive.

It was pointed out recently [2] (see also [3] for an earlier discussion) that transverse polarization can play a unique role in isolating chirality violating couplings, to which processes with longitudinally polarized beams are not sensitive. The interference of new chirality-violating contributions with the chirality-conserving standard model (SM) couplings give rise to terms in the angular distribution proportional to $\sin\theta\,\cos\phi$ and $\sin\theta\,\sin\phi$, where θ and ϕ are the polar and azimuthal angles of a final-state particle. Chirality conserving new couplings, on the other hand, produce interference contributions proportional to $\sin^2\theta\,\cos 2\phi$ and $\sin^2\theta\,\sin 2\phi$. Chirality-violating contributions do not interfere with the chirality-conserving SM contribution with unpolarized or longitudinally polarized beams when the electron mass is neglected. Hence transverse polarization would enable measurement of chirality-violating couplings through the azimuthal distributions.

A general discussion of azimuthal distributions and asymmetries arising with transverse beam polarization in the context of CP violation was presented in [2], and illustrated by means of the process $e^+e^- \to t\bar{t}$ in the presence of general contact interactions. It is difficult to come by models where chirality violating couplings which produce the specific azimuthal distributions mentioned above are present at low orders of perturbation. In this paper, we examine a specific model where chirality-violating couplings occur at tree level, viz., a scalar leptoquark model. In this model, there is an $SU(2)_L$ doublet of scalar leptoquarks, which couples only to first-generation leptons and third-generation quarks. Since couplings of leptoquarks to the third generation quarks are relatively weakly constrained, their effect in $e^+e^- \to t\bar{t}$ is expected to be non-negligible. This model has been chosen mainly for purposes of illustration of the ideas in [2], and we find that transverse polarization can indeed be used to put direct constraints on such a model. It would be interesting to look for the azimuthal asymmetries described here if a future linear collider can be equipped with transversely polarized beams.

We allow leptoquark couplings of both left and right chiralities, and also allow them to be complex. Thus, the possibility of CP violation is kept open.

We then show how azimuthal asymmetries of the top quarks in the process $e^+e^- \to t\bar{t}$ with transversely polarized beams can be used to measure the phases of the couplings.

2 The model

We now go to the details of the model. We assume that SM with its gauge group $SU(2)_L \times U(1) \times SU(3)_C$ is extended by a multiplet ϕ of scalar leptoquarks transforming according to the representation $(\underline{2}, -\frac{7}{6}, \underline{3}^*)$ of the gauge group. Assuming ϕ to couple only to first generation leptons and third generation quarks, its couplings to the fermions can be written as

$$\mathcal{L}_\phi = h_{2L} \bar{l}_L u_R \phi + h_{2R}^* \bar{q}_L i\tau_2 e_R \phi^* + \text{H.c.}, \tag{1}$$

where

$$l_L \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad q_L \equiv \begin{pmatrix} t \\ b \end{pmatrix}_L, \tag{2}$$

are left-handed doublets. The representation for ϕ has been chosen so that it can contribute to the process

$$e_L^- e_L^+ \to t_R \bar{t}_R$$

and

$$e_R^- e_R^+ \to t_L \bar{t}_L$$

by a t-channel exchange. In SM, on the other hand, s-channel exchange of γ and Z contributes only to

$$e_L^- e_R^+ \to t\bar{t}$$

and

$$e_R^- e_L^+ \to t\bar{t}.$$

In the above, the subscripts L, R denote chiralities. Since we will neglect the electron mass, these will be identical to helicities so far as the e^+ and e^- are concerned.

It is possible to choose a scalar leptoquark multiplet transforming as $(\underline{1}, \frac{1}{3}, \underline{3}^*)$, which satisfies the conditions stated above. The corresponding couplings would be fermion-number violating. We refer the reader to [4] for a general discussion of leptoquark models, and to [5] for a brief review of quantum numbers. However, the results so far as azimuthal distributions are concerned would be analogous to the case we treat here.

3 The process $e^+e^- \to t\bar{t}$

The amplitude for the process

$$e^-(p_1, s_1) + e^+(p_2, s_2) \to t(k_1) + \bar{t}(k_2), \tag{3}$$

with the couplings of $\mathcal{L}_\phi$, in addition to SM couplings, is

$$M = M_1 + M_2, \tag{4}$$

where the SM contribution is

$$\begin{aligned} M_1 &= e\left[\frac{2}{3}\overline{u}(k_1)\gamma^\mu v(k_2)\frac{1}{q^2}\overline{v}(p_2, s_2)\gamma_\mu u(p_1, s_1) + \overline{u}(k_1)\gamma^\mu(g_V^t - g_A^t\gamma_5)v(k_2)\right. \\ &\quad \left. \times\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{m_Z^2}\right)\frac{1}{q^2 - m_Z^2}\overline{v}(p_2, s_2)\gamma^\nu(g_V^e - g_A^e\gamma_5)u(p_1, s_1)\right], \end{aligned} \tag{5}$$

where $q = p_1 + p_2 = k_1 + k_2$. The contribution M_2 coming from t-channel leptoquark exchange is

$$M_2 = e\Big[\overline{u}(k_1)(g_L P_L + g_R P_R)u(p_1, s_1)\frac{1}{t - M^2}\overline{v}(p_2, s_2)(g_L^* P_R + g_R^* P_L)v(k_2)\Big], \tag{6}$$

where we have used the notation $h_{2L,R} = eg_{L,R}$, $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$, and M is the mass of the leptoquark exchanged. The couplings to Z of the fermions are given by

$$g_V^e = -\tfrac{1}{4} + \sin^2\theta_W, \quad g_A^e = -\tfrac{1}{4}, \tag{7}$$

$$g_V^t = \tfrac{1}{4} - \tfrac{2}{3}\sin^2\theta_W, \quad g_A^t = \tfrac{1}{4}. \tag{8}$$

We assume transverse polarizations P_1 and P_2 of the e^- and e^+ beams, respectively, which are assumed to be parallel to each other, apart from a possible sign. We can then use simple Dirac algebra to obtain the cross section as the sum of the SM contribution $\sigma_{\rm SM}$, the pure leptoquark contribution $\sigma_{\rm LQ}$, and the contribution $\sigma_{\rm int}$ from the interference of the leptoquark contribution with the SM contribution. We can write the differential cross section as

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\rm SM}}{d\Omega} + \frac{d\sigma_{\rm LQ}}{d\Omega} + \frac{d\sigma_{\rm int}}{d\Omega}. \tag{9}$$

Here the SM differential cross section is itself the sum of the γ contribution, the Z contribution, and the γZ interference contribution:

$$\frac{d\sigma_{\rm SM}}{d\Omega} = \frac{d\sigma_{\rm SM}^\gamma}{d\Omega} + \frac{d\sigma_{\rm SM}^Z}{d\Omega} + \frac{d\sigma_{\rm SM}^{\gamma Z}}{d\Omega}, \tag{10}$$

where

$$\frac{d\sigma^{\gamma}_{\rm SM}}{d\Omega} = \frac{\alpha^2\beta}{3s}\left[2-(1+P_1P_2)\beta^2\sin^2\theta+2P_1P_2\beta^2\sin^2\theta\cos^2\phi\right], \tag{11}$$

$$\begin{aligned}\frac{d\sigma^{Z}_{\rm SM}}{d\Omega} &= \frac{3\alpha^2\beta s}{4(s-m_Z^2)^2}\left[(g_V^{t\,2}+g_A^{t\,2})\left\{(g_V^{e\,2}+g_A^{e\,2})-(g_V^{e\,2}-g_A^{e\,2})P_1P_2\beta^2\right\}\right.\\ &\quad +(g_V^{t\,2}-g_A^{t\,2})(g_V^{e\,2}+g_A^{e\,2})(1-\beta^2)+8g_V^tg_A^tg_V^eg_A^e\beta\cos\theta\\ &\quad +(g_V^{t\,2}+g_A^{t\,2})\left\{(g_V^{e\,2}+g_A^{e\,2})+(g_V^{e\,2}-g_A^{e\,2})P_1P_2\right\}\beta^2\cos^2\theta\\ &\quad \left.+2(g_V^{t\,2}+g_A^{t\,2})(g_V^{e\,2}-g_A^{e\,2})P_1P_2\beta^2\sin^2\theta\cos^2\phi\right],\end{aligned} \tag{12}$$

$$\begin{aligned}\frac{d\sigma^{\gamma Z}_{\rm SM}}{d\Omega} &= -\frac{\alpha^2\beta}{s-m_Z^2}\left[g_V^eg_V^t\left\{2-(1+P_1P_2)\beta^2\sin^2\theta\right\}\right.\\ &\quad \left.+\,2g_A^eg_A^t\beta\cos^2\theta+2g_V^eg_V^tP_1P_2\beta^2\sin^2\theta\cos^2\phi\right].\end{aligned} \tag{13}$$

The pure leptoquark contribution is given by

$$\frac{d\sigma_{\rm LQ}}{d\Omega} = \frac{3\alpha^2\beta s}{64(t-M^2)^2}\left(|g_L|^2+|g_R|^2\right)^2(1-\beta\cos\theta)^2. \tag{14}$$

The contribution from the interference between the leptoquark and the SM γ and Z diagrams is, respectively,

$$\frac{d\sigma^{\gamma}_{\rm int}}{d\Omega} = \frac{\alpha^2\beta}{8(t-M^2)}\left(|g_L|^2+|g_R|^2\right)\left\{(P_1P_2\cos2\phi-1)\beta^2\sin^2\theta+2-2\beta\cos\theta\right\}, \tag{15}$$

and

$$\begin{aligned}\frac{d\sigma^{Z}_{\rm int}}{d\Omega} &= -\frac{3\alpha^2\beta s}{16(s-m_Z^2)(t-M^2)}\Big[|g_R|^2\Big\{P_1P_2\beta^2(g_V^e-g_A^e)(g_V^t-g_A^t)\sin^2\theta\cos2\phi\\ &\quad +(g_V^e+g_A^e)(g_V^t+g_A^t)(1-\beta^2)+(g_V^e+g_A^e)(g_V^t-g_A^t)(1-\beta\cos\theta)^2\Big\}\\ &\quad +|g_L|^2\Big\{P_1P_2\beta^2(g_V^e+g_A^e)(g_V^t+g_A^t)\sin^2\theta\cos2\phi\\ &\quad +(g_V^e-g_A^e)(g_V^t-g_A^t)(1-\beta^2)+(g_V^e-g_A^e)(g_V^t+g_A^t)(1-\beta\cos\theta)^2\Big\}\\ &\quad +4m_t\sqrt{s}\beta(g_V^eg_A^t+g_A^eg_V^t)\sin\theta\,\{(P_1+P_2){\rm Re}\,(g_Rg_L^*)\cos\phi\\ &\quad +\,(P_1-P_2){\rm Im}\,(g_Rg_L^*)\sin\phi\}\Big].\end{aligned} \tag{16}$$

In the above, $t = (p_1 - k_1)^2 = m_t^2 - \frac{s}{2}(1 - \beta\cos\theta)$.

It can be seen from these equations that the interference term between the SM Z contribution and the leptoquark contribution contains terms proportional to $\sin\theta\,\cos\phi$ and $\sin\theta\,\sin\phi$, which are linear in P_1 and P_2, and are proportional respectively to the real and imaginary parts of $g_R g_L^*$. Both these require the simultaneous presence of couplings of both chiralities. The term containing $\sin\theta\,\sin\phi$ is a measure of CP violation, and is nonzero only if g_L and g_R are relatively complex. These terms do not need both e^- and e^+ beams to be polarized. There are also terms in the differential cross section proportional to $\sin^2\theta\sin 2\phi$ and $\sin^2\theta\cos 2\phi$, which are proportional to P_1P_2, and to $|g_L|^2$ or $|g_R|^2$. They are present even if leptoquark coupling of only one chirality is present, but require both e^- and e^+ beams to be polarized. These absolute values of chiral couplings are also the ones that can be studied using longitudinal polarization, because in that case the interference between different chirality contributions vanish in the limit of vanishing electron mass.

The chirality violating terms can be isolated by studying the following azimuthal asymmetries, where we assume θ to be integrated over with a cut-off θ_0 in the forward and backward directions:

$$A_1(\theta_0) = \frac{1}{\sigma(\theta_0)} \int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \left[\int_0^{\pi} d\phi - \int_{\pi}^{2\pi} d\phi\right] \frac{d\sigma}{d\Omega}, \tag{17}$$

$$A_2(\theta_0) = \frac{1}{\sigma(\theta_0)} \int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \left[\int_{-\pi/2}^{\pi/2} d\phi - \int_{\pi/2}^{3\pi/2} d\phi\right] \frac{d\sigma}{d\Omega}, \tag{18}$$

where

$$\sigma(\theta_0) = \int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \int_0^{2\pi} d\phi\, \frac{d\sigma}{d\Omega}. \tag{19}$$

The expressions for A_1 and A_2 in the leading order, where terms quartic in the leptoquark couplings are neglected, are as follows:

$$\begin{aligned} A_1(\theta_0) &= \frac{1}{\sigma_{\rm SM}(\theta_0)} (P_1 - P_2) \left(g_V^e g_A^t + g_A^e g_V^t\right) \mathrm{Im}(g_R g_L^*) \frac{6\alpha^2 m_t}{s^{3/2}(s - m_Z^2)} \\ &\times \left[C(\pi - 2\theta_0) - 2\sqrt{C^2 - s^2\beta^2}\tan^{-1}\left(\frac{\sqrt{C^2 - s^2\beta^2}}{C}\cot\theta_0\right)\right], \end{aligned} \tag{20}$$

$$\begin{aligned} A_2(\theta_0) &= \frac{1}{\sigma_{\rm SM}(\theta_0)} (P_1 + P_2) \left(g_V^e g_A^t + g_A^e g_V^t\right) \mathrm{Re}(g_R g_L^*) \frac{6\alpha^2 m_t}{s^{3/2}(s - m_Z^2)} \\ &\times \left[C(\pi - 2\theta_0) - 2\sqrt{C^2 - s^2\beta^2}\tan^{-1}\left(\frac{\sqrt{C^2 - s^2\beta^2}}{C}\cot\theta_0\right)\right], \end{aligned} \tag{21}$$

where $C = 2M^2 - 2m_t^2 + s$, and $\sigma_{\rm SM}(\theta_0)$ is the SM cross section with the cut-off θ_0, which may be easily evaluated by an appropriate integration of $d\sigma_{\rm SM}/d\Omega$ in eq. (10). It can be seen from eqs. (20) and (21) that $A_1(\theta_0)$ and $A_2(\theta_0)$ differ only in the factors $(P_1 - P_2)\,{\rm Im}(g_R g_L^*)$ and $(P_1 + P_2)\,{\rm Re}(g_R g_L^*)$. The two asymmetries, therefore, will have identical dependence on the SM parameters and kinematic variables.

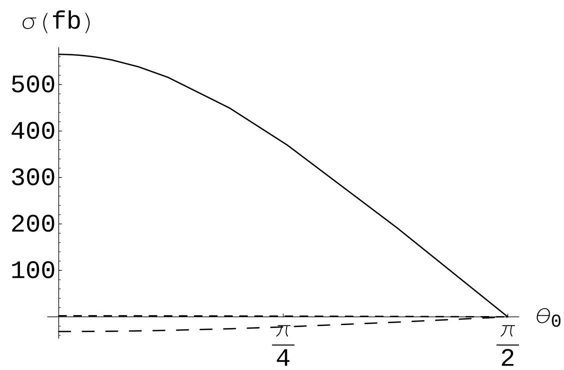

Figure 1: The various contributions to the total cross section with a cut-off θ_0 for values $g_L = g_R = 1/\sqrt{2}$, and leptoquark mass $M = 1000$ GeV. The solid curve is the SM contribution, the long-dashed curve the interference between the SM and leptoquark contributions, and the short-dashed curve is the pure leptoquark contribution.

4 Numerical Results

We now come to the numerical results. For our calculations we use $\alpha = 1/128$, $m_Z = 91.1876$ GeV, $m_t = 174$ GeV, and $\sin^2\theta_W = 0.233$. We assume a cm energy of $\sqrt{s} = 500$ GeV, a linear collider with e^- polarization 80%, e^+ polarization 60%, and an integrated luminosity of 500 fb^{-1}.

In Fig. 1 we show the different contributions to the total cross section with a cut-off θ_0 for values $g_L = g_R = 1/\sqrt{2}$, and leptoquark mass $M = 1000$ GeV. The solid curve is the SM contribution, the long-dashed curve the interference between the SM and leptoquark contributions, which is approximately the

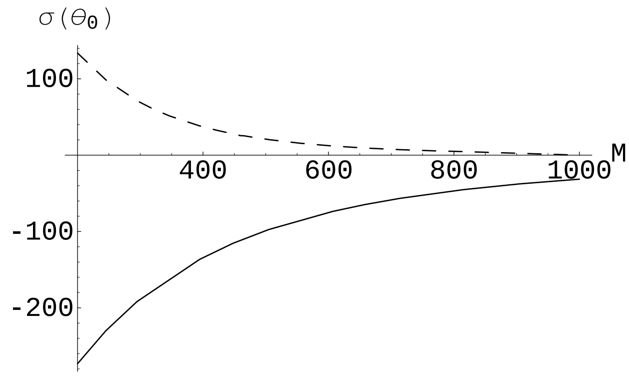

Figure 2: The interference (solid curve) and pure leptoquark contributions (dashed curve) to the cross section as a function of the leptoquark mass M (in GeV), for a fixed value of cut-off, $\theta_0 = 0.1$ radians. The other parameters are as in Fig. 1

total new-physics contribution, since the pure leptoquark contribution (short-dashed curve) is negligible. The cross sections in Fig. 1 are independent of transverse polarization. They show a monotonic decrease with θ_0, as expected.

Fig. 2 shows the interference between the SM and leptoquark amplitudes (solid curve), and pure leptoquark contributions (dashed curve) to the cross section as a function of the leptoquark mass M (in GeV), for a fixed value of cut-off, $\theta_0 = 0.1$ radians. The other parameters are as in Fig. 1. As expected, the leptoquark contribution decreases with M.

Fig. 3 depicts the asymmetry $A_1(\theta_0)$ as a function of θ_0 for the values $P_1 = 0.8$, $P_2 = -0.6$, $g_L = 1/\sqrt{2}$, $g_R = i/\sqrt{2}$ and $M = 1000$ GeV. The values of the couplings correspond to maximal CP violation in the leptoquark couplings. The asymmetry is of the order of 4×10^{-3}, and is not very sensitive to the cut-off.

In view of the remark made earlier, Fig. 3 also shows the asymmetry $A_2(\theta_0)$ for the values $P_1 = 0.8$, $P_2 = 0.6$, $g_L = 1/\sqrt{2}$, $g_R = 1/\sqrt{2}$ and $M = 1000$ GeV. In this case, there is no CP violation, and the sign of P_2 is chosen positive to maximize the asymmetry.

We plot in Fig. 4 the asymmetry $A_1(\theta_0)$ (or $A_2(\theta_0)$ with a suitable change

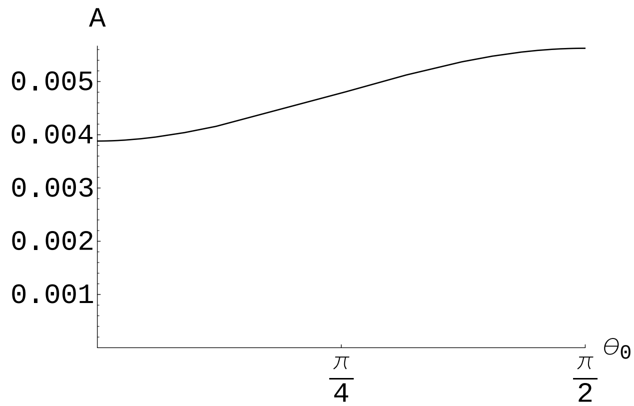

Figure 3: The asymmetry $A_1(\theta_0)$ as a function of θ_0 for the values $P_1 = 0.8$, $P_2 = -0.6$, $g_L = 1/\sqrt{2}$, $g_R = i/\sqrt{2}$ and $M = 1000$ GeV. The same curve also shows $A_2(\theta_0)$ for $g_L = 1/\sqrt{2}$, $g_R = 1/\sqrt{2}$, and $P_2 = 0.6$.

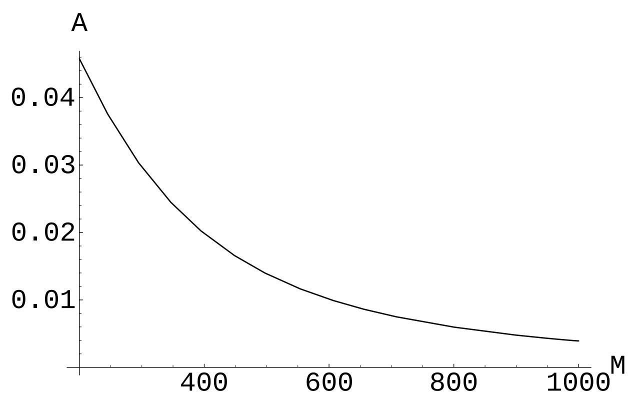

Figure 4: The asymmetry $A_1(\theta_0)$ as a function of M (in GeV) for the values $P_1 = 0.8$, $P_2 = -0.6$, $g_L = 1/\sqrt{2}$, $g_R = i/\sqrt{2}$, and $\theta_0 = 0.1$ radians. The same curve also shows $A_2(\theta_0)$ for $g_L = 1/\sqrt{2}$, $g_R = 1/\sqrt{2}$ and $P_2 = 0.6$.

of parameters) as a function of M for $\theta_0 = 0.1$ radians.

We show in Fig. 5 the 90% confidence level (CL) limit $g_{\rm lim}$ that can be put on the combinations $\mathrm{Im}(g_R g_L^*)$ (in the maximal CP violation case) and $\mathrm{Re}(g_R g_L^*)$ (in the CP conservation case) for $M = 1000$ GeV. This limit

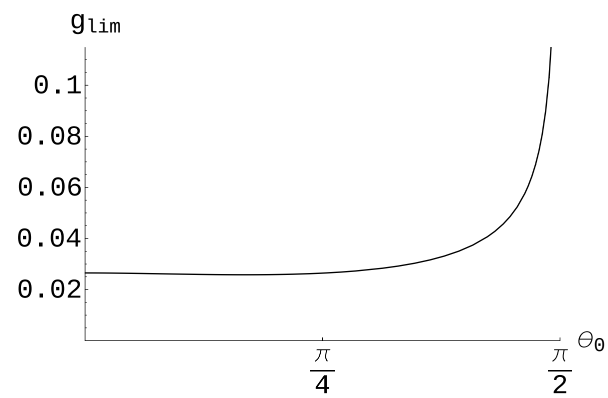

Figure 5: The 90% CL limit $g_{\rm lim}$ that can be obtained on $\mathrm{Re}(g_R g_L^*)$ or $\mathrm{Im}(g_R g_L^*)$ respectively from A_1 or A_2 for an integrated luminosity of 500 fb^{-1} plotted as a function of θ_0.

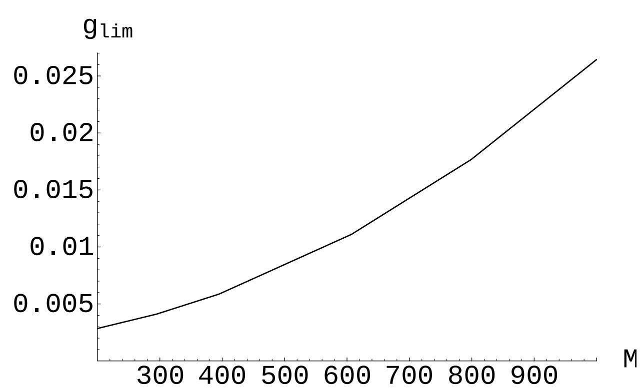

Figure 6: The 90% CL limit $g_{\rm lim}$ that can be obtained on $\mathrm{Re}(g_R g_L^*)$ or $\mathrm{Im}(g_R g_L^*)$ respectively from A_1 or A_2 for an integrated luminosity of 500 fb^{-1} plotted as a function of M (in GeV).

is obtained by equating the asymmetry to $1.64/\sqrt{N_{\rm SM}}$, where $N_{\rm SM}$ is the number of SM events, $N_{\rm SM} = \sigma_{\rm SM}(\theta_0)\, L$, L being the integrated luminosity. It can be seen that the possible limit $g_{\rm lim}$ on $\mathrm{Re}(g_R g_L^*)$ or $\mathrm{Im}(g_R g_L^*)$ is about 0.025 for most values of $\theta_0 \leq \pi/4$. Fig. 6, which contains a plot of $g_{\rm lim}$ as

a function of M for $\theta_0 = 0.1$ radians, shows that this limit can improve for lower values of M, reaching about 0.005 for $M \approx 300$ GeV.

5 Discussion

We now present a discussion of these results. First of all, we need to review the present limits on the couplings and mass of the leptoquarks. Since we consider specifically leptoquarks coupling only to third-generation quarks, the direct limits are rather weak [6]. In general, they seem to allow a leptoquark mass of about 200 GeV for coupling strengths of the order of electroweak coupling. Strong indirect limits may, however, be obtained especially in our case where the leptoquark has both left- and right-handed couplings. Detailed discussion on indirect limits may be found in [7]. The most stringent limits come from dipole moments of the electron. Requiring the contribution to the electron $g-2$ coming from one-loop diagrams with top and leptoquark internal lines

$$g_e - 2 \approx \frac{\alpha}{2\pi}\frac{m_e m_t}{M^2}\ln\frac{m_t^2}{M^2}\mathrm{Re}(g_R g_L^*) \tag{22}$$

to be less than the experimental uncertainty of 8×10^{-12} gives

$$\frac{\mathrm{Re}(g_R g_L^*)}{(M/\mathrm{TeV})^2} < 0.1. \tag{23}$$

The limits obtainable from our asymmetry A_2 are clearly better than this.

The contribution to the electric dipole moment d_e of the electron from the same one-loop diagrams is

$$d_e \approx \frac{\alpha}{2\pi}\frac{m_t}{M^2}\ln\frac{m_t^2}{M^2}\mathrm{Im}(g_R g_L^*). \tag{24}$$

It is clear that the direct limit obtainable from A_1, viz., $\mathrm{Im}(g_R g_L^*) < 0.025$ for $M = 1$ TeV, is nowhere near the much more stringent limit obtained from the experimental limit of about 10^{-27} e cm on d_e, which leads to

$$\frac{\mathrm{Im}(g_R g_L^*)}{(M/\mathrm{TeV})^2} < 10^{-6}. \tag{25}$$

In conclusion, we have pointed out azimuthal asymmetries which single out products of opposite-chirality couplings of scalar leptoquarks and which

can provide a direct test of these in linear collider experiments. Longitudinal beam polarization, on the other hand, can only put limits on the absolute values of the left and right chiral couplings. The limit that can be put on real part of the product of the couplings $g_R g_L^*$ is about 0.025 for reasonable values of linear collider parameters, and assuming a leptoquark mass of about 1 TeV. This limit is better than the indirect limit from the $g-2$ of the electron. It would be interesting to look for the asymmetry A_2 if transverse polarization is available at a future linear collider. The imaginary part of this product can in principle be constrained by a suitable CP-violating azimuthal asymmetry to the same extent. However, the much better experimental limit on the electric dipole of the electron already makes such a limit redundant.

The discussion here can be extended to scalar leptoquarks transforming as $(\underline{1}, \frac{1}{3}, \underline{3}^*)$ representation of the gauge group with similar conclusions.

Acknowledgements This work is supported by the Department of Science and Technology (DST), Government of India, under project number SP/S2/K-01/2000-II. The author thanks B. Ananthanarayan and Rohini Godbole for discussions, and Ananthanarayan also for a careful reading of the manuscript.

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